70th International Astronautical Congress (IAC), Washington, D.C., USA, 21-25 October 2019.

IAC-19,A3,IP,22,x53658

DEVELOPMENT AND TEST OF A FOLDABLE PROTECTION SYSTEM FOR A SMALL LANDING PROBE USING 3D-PRINTED METAL GRIDS AS SHOCK ABSORBER

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The exploration of our solar system has progressed continuously during the past decades. Here, especially the planets stood in the foreground of investigation. But in order to study the formation of the solar system and the evolution of life within the focus has shifted now also to smaller bodies like comets, asteroids and smaller moons of the planets. All those objects have similarities with regard to their weak gravitational field and their absence of an atmosphere. Small landing probes in the range of less than 20kg therefore face the challenge of landing without the help of a parachute and possibly without a propulsion system.

A suitable technique for protecting a lander from the shock of impact is a crushable shell, which absorbs the kinetic energy at touchdown by plastic deformation of its core material. Past studies revealed the effectiveness of this method, which has also been used for the landing probe Schiaparelli of the ESA Trace Gas Orbiter. But landing probes like Schiaparelli rely on an active Guidance, Navigation & Control (GNC) system to keep its right orientation, since the shell is only on the bottom side of the lander. A less complex and lightweight solution could be to cover all sides of the lander and thus to omit the GNC and propulsion system completely.

The obvious challenge with this kind of design is the need for an unfolding mechanism, which would remove the crushed shell elements from the lander body in order to have a free and unobscured field of view for the instruments and antennas.

Another innovative design concept is the use of a core made of 3D-printed metal grids instead of commonly used aluminum honeycombs as the primary shock absorbers. The advantage of the metal grids is the multi-directional energy absorption capability which is not given with the honeycomb. With this feature the lander can land in any inclination without losing crash performance.

In this paper we present and discuss the design, manufacturing process and breadboard testing of a small landing probe encapsulated in a crushable shell made out of 3D-printed metal grids core and GFRP face sheets.

I. INTRODUCTION

In the framework of a research project, called "Orbitallander", a weight optimized landing system has been developed to land a small spacecraft without propulsion system at high speed (up to 4m/s) on a medium sized airless body.

Based on representative requirements from current and upcoming missions, the landing concept is orientated on the asteroid lander MASCOT (Fig. 1).

Fig. 1: Artist view of MASCOT and Hayabusa-2 (credit: DLR)

MASCOT had a weight of 10kg and overall dimensions of 300x300x200mm³ [1]. It touched down (162173) Ryugu on October 3rd 2018 with only a few cm/s since this asteroid is only 900m in diameter and has a very low gravitational field. Therefore, the lander didn't need a dedicated landing system.

A possible successor shall land on larger bodies like the moons of Mars, which already have a significant gravitation that in turn leads to higher landing velocities in free fall. The lander needs to be protected from the shock of impact by a crushable shell, which absorbs the kinetic energy at touchdown by plastic deformation of its core material. This core material can be aluminum honeycombs, as it has been used in former studies [2][3], but the disadvantage of this method is that it mainly absorbs energy in its primary cell direction, which usually is aligned along the thickness of the shell. This, however, may be sub-optimal for inclined landing cases. By replacing the honeycombs with 3D-printed metal grids this phenomenon can be suppressed. A schematic view of the lander with surrounded crash panels or cushions can be seen in Fig. 2.

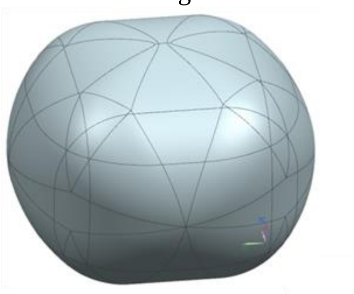

Fig. 2: CAD-view of the outer shell of the lander

For comparison the outer shape of the lander was identical to the test specimen from the previous campaign with aluminum honeycomb core [see 1].

II. DEVELOPMENT OF THE CRASH CELL

The use of 3D-printed metal grids is an innovative application. So in the first step the right material and design had to be defined. The geometry of the unit cell consists of diagonal beams with a diameter of 1mm, which was the thinnest thickness possible with the available printers. The size of the reference test specimen was set to be 50x50x50mm. In Fig. 3 the geometrical construction is symbolized.

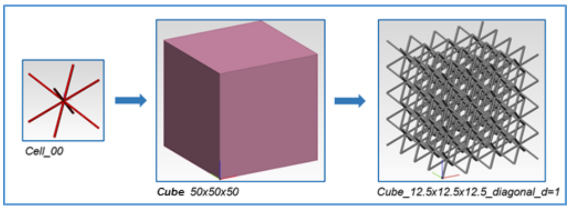

Fig. 3: Unit cell "diagonal" with element size 12.5x12.5x12.5mm

Several uniform units have been printed by varying the material and size of the cells to find out the best characteristics. Three kinds of metal have been considered: a) aluminum (AlSi10Mg), b) stainless steel (SS316L) and c) titanium (Ti6Al4V).

The test specimens were tested under uniaxial compression loading in a universal testing machine as can be seen in Fig. 4 with the aim to evaluate the crushing ability of the different materials.

Fig. 4: Unit cell in a universal testing machine

The first tests showed that aluminum and titanium were too brittle (the beams broke instead of deform plastically). As a consequence, from the tested materials only stainless steel was considered for further investigation.

In further analyses the optimal cell size was determined by using a combination of hardware testing and simulations. For the hardware tests the cell size has been varied between 12.5mm and 25mm. With those results the simulation could be calibrated and a test prediction could be calculated.

For simulating the impact of the landing probe the program Abaqus has been used. The design was taken from the CAD file of the lander.

The optimization was done by assessing the two critical load cases:

1. landing on a flat plain → max. acceleration
2. landing on an obstacle → max. deformation

Both landing cases were simulated with 4m/s vertical velocity and a system mass of 15kg. An optimized cell should have the lowest maximal acceleration without having a deformation larger than 70% of the sample length.

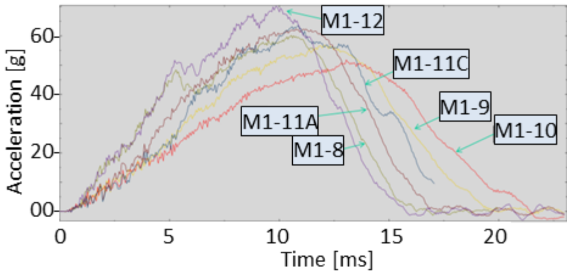

Fig. 5: Acceleration plot of various cell sizes for impact on a flat plain

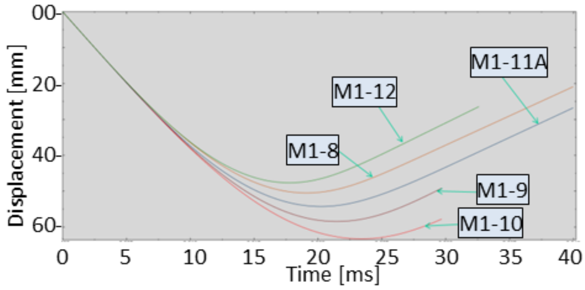

Fig. 6: Deformation of various cell sizes for impact on an obstacle

The simulation showed that the cell M1-10 (23mm element size) had the best performance with regard to maximum acceleration (a_{max}=53g) and deformation (z_{max}=69mm).

III. DEVELOPMENT OF AN OPENING MECHANISM

For an unrestricted performance of the landers scientific instruments as well as for its communication elements the crash panels need to be detached after landing. For this purpose an unfolding mechanism has been developed, which unfolds five of the six sides of the lander. The bottom side shall remain on the lander. For a stationary probe it is advantageous to cover the inside of the crash panels with solar cells for power supply. A requirement was therefore to keep the panels physically connected to the lander. This issue has been solved by installing a torsion spring mechanism in the joints between two crash panels. A principle of the system can be seen in Fig. 7.

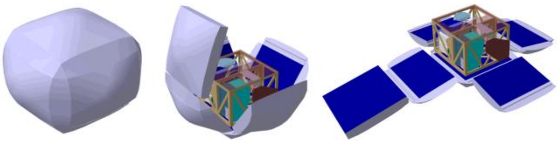

Fig. 7: Principle of unfolding the crash panels from the lander

The unfolding of the crash panels requires a shift of the pivot point, which is on the inner side of the panels. Otherwise the crash panels would collide during the unfolding process. The shift of the pivot point is realized by another spring which pushes the torsion spring to the outside. This spring and the torsion spring are made of one piece and bent so that when folded they are held in place within a thin double bottom at the lander. For each side panel the corresponding device is fixed at the base plate. A schematic view of the spring system can be seen in Fig. 8.

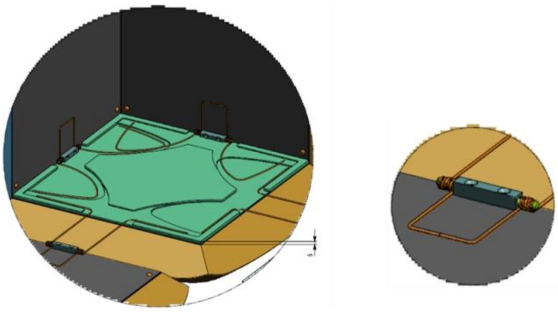

Fig. 8: Spring system: (left) springs for shifting the fulcrum, (right) torsion spring for turning the panel

Since the spring geometries overlap when folded up, the bottom panel is equipped with two levels arranged one above the other, which are separated from each other by a thin intermediate plate. To open the lid panel, the spring mechanism - analogous to the side panels opening spring mechanisms - is embedded in the base of one of the side cushions.

The spring mechanism is loaded when the lander is closed and relaxed when it is open. Due to the design, the spring mechanism will float when the lander is open. This allows the cushion cover alignment to adapt to deformations of the crash panels. This would not be the case with a fixed bearing and the deployment process could be impeded. The selected configuration is therefore favorable in order to prevent unintended tilting.

By using a spring mechanism, however, an actuator must be used to hold the preloaded elements in their respective nominal position before the opening process.

The cushions are locked in the center by pins on the lander side, which move into corresponding lugs on the inside of the cushions.

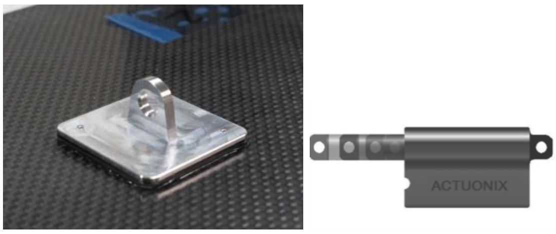

Fig. 9:(left) locking lug on the CFRP base of a panel cover, (right) locking actuator

Linear servos lock the panels to cross struts in which slots are provided for the flaps (Fig. 9). This allows for a fixed lock that can be opened by actuating the linear servos.

Respective stand-off elements at the corners of the panels' base plates provide position guidance and well as lateral stability during the impact event. In Fig. 10 and Fig. 11 the whole system can be seen.

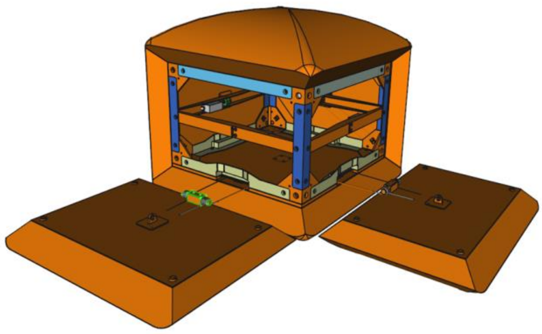

Fig. 10: Partially opened lander

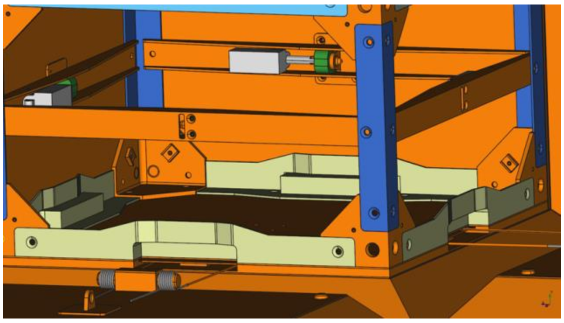

Fig. 11: Detailed view of the lock & release mechanism

IV. TEST SETUP

In an experimental investigation, the entire system had to pass through realistic landing conditions and then demonstrate error-free unfolding. For this purpose, the test object has been implemented in a test rig and was subjected to impact conditions equivalent to the ones used in the previous simulation - either hitting a flat plate (in the following called deflector) or impactor (in the following called penetrator) in different positions.

In order to counteract Earth' gravity, the lander this test rig was designed as a pendulum with a parallel kinematic, which has the advantage that the base is always horizontal (Fig. 12). This ensures that the test specimen hits the obstacle in a precisely defined position.

For further details on the physics of this pendulum test rig and setup please refer to [3].

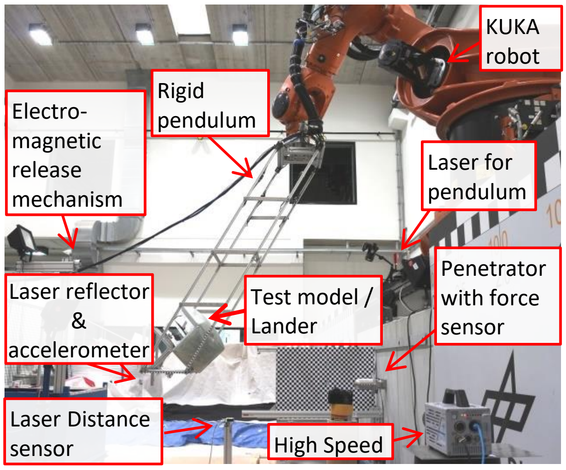

Fig. 12: Test Setup

The test stand has also been equipped with sensors that enable precise analysis. These included force, acceleration and displacement transducers in order to make qualitative statements about the performance of the crash cushions. Video cameras also documented the tests.

The test plan is shown below (Table 1). Due to the small number of crash cushions, only a limited number of tests could be performed. These are divided into three parts. The first three tests were performed on an unused crash panel. The deformation influence zones have then been evaluated and a decision was made if further tests were possible on the edges, i.e. the interfaces between two cushions. Since only slight deformations occurred here, a corner could be tested in a seventh test and also a second test run for a short edge by changing the deflector with the penetrator.

Test No.	Impact velocity [m/s]	Impact side	Orientation	Impactor
1	4	S1	side	def
2	4	S2	side	pen
3	3	T1	top	pen
4	4	S1/T1	long edge	pen
5	4	S2/T1	long edge	def
6	4	S1/S2	short edge	def
7	4	S1/S2/T1	corner	pen
8	4	S1/S2	short edge	pen

Table 1: Pendulum test plan (def=deflector, pen=penetrator)

The setup has been trimmed to a "reduced mass" (theory of a physical pendulum) of 15kg. Since the mass of the aluminum-bars contributes partially to the kinetic energy of the impact, the value of the reduced mass is equivalent to the mass acting during impact defining the kinetic energy.

V. TEST EXECUTION

Tests have been performed in the DLR's Landing & Mobility Test Facility (LAMA), Bremen, Germany using the robot to positioning the pendulum to the right impact point.

The impact velocity has been adjusted by the deflection of the pendulum.

The most significant parameters for the performance of the crash panels were the acceleration progression and the maximum deformation. In Fig. 13 and Fig. 14 example plots are given from test no.2.

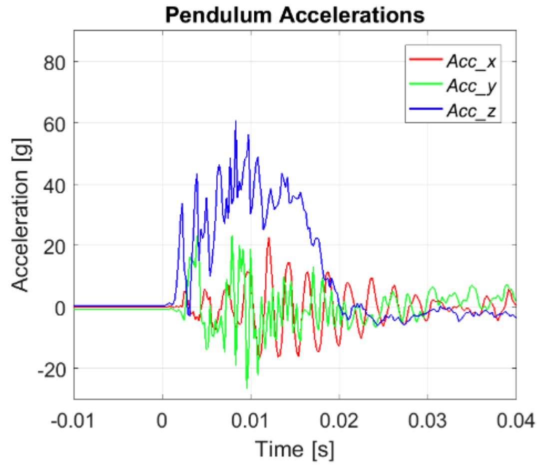

Fig. 13: Acceleration plot of test no. 2

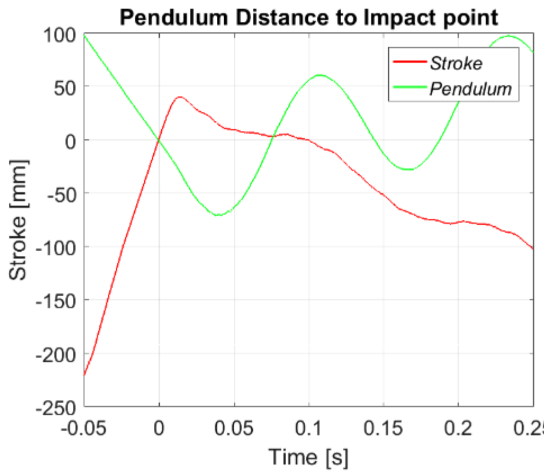

Fig. 14: Stroke plot of test no. 2

The blue line in Fig. 13 marks the accelerometer reading in impact direction and one can see that the impact takes about 20ms with the maximum acceleration in the center. The strong fluctuation in the rise of the acceleration stems from the core and corresponds to periodic bending of the inner beams.

The red line in the stroke plot shows the sinkage of the cushion into the obstacle. The green line shows the maximum deflection at the center of the 2m long pendulum. This value is necessary to determine how much energy is transferred into the pendulum after impact and does not contribute to the energy absorption for the crash panel.

In Fig. 15 one can see a sequence of an impact.

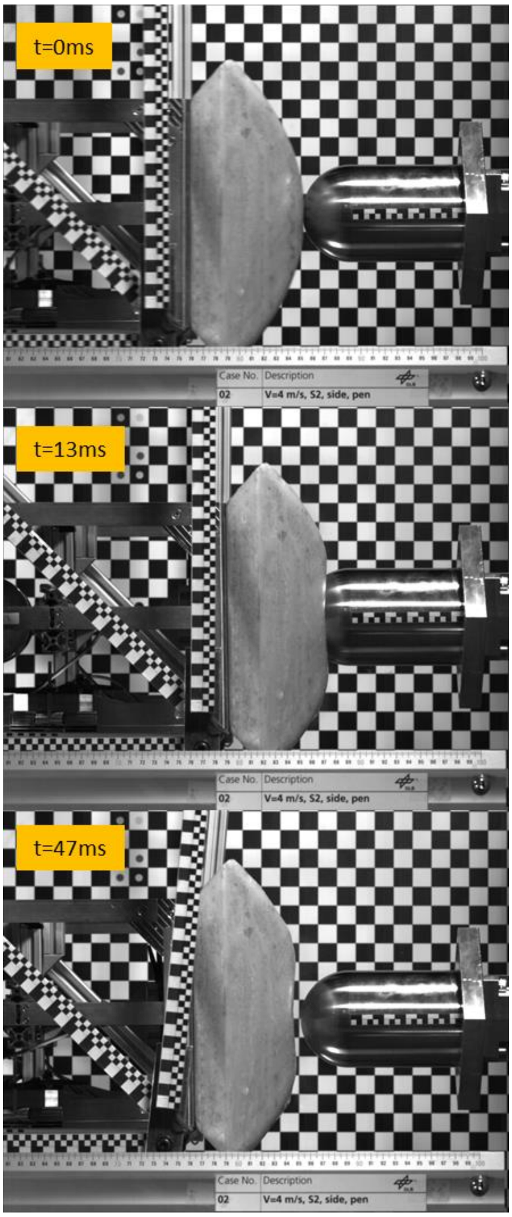

Fig. 15: Test sequence of test no. 2

After each test the shell opening has been demonstrated. In Fig. 16 a typical sequence of an unfolding can be seen.

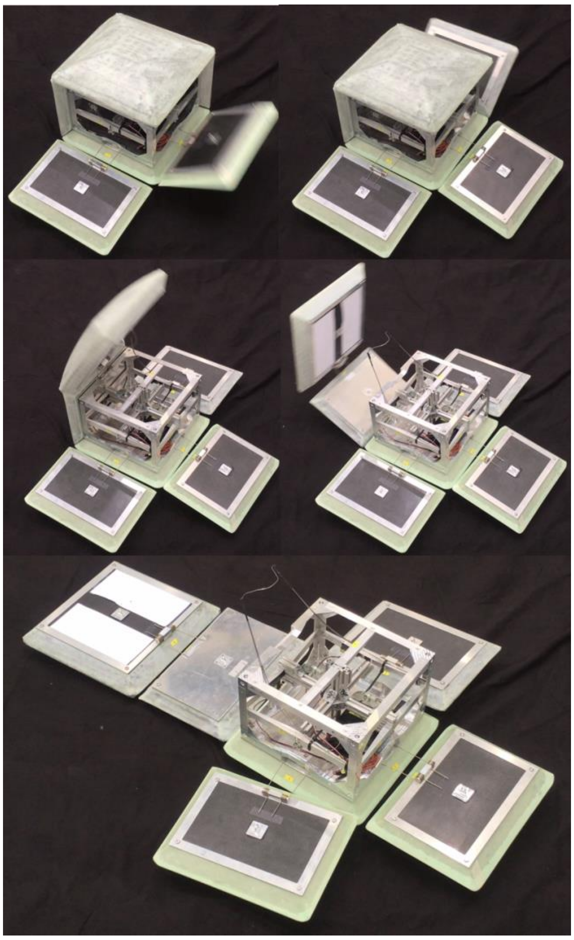

Fig. 16: Sequence of an opening

VI. TEST RESULTS

In Fig. 17 and Fig. 18 the maximum impact stroke and respective maximum acceleration of each test case are depicted.

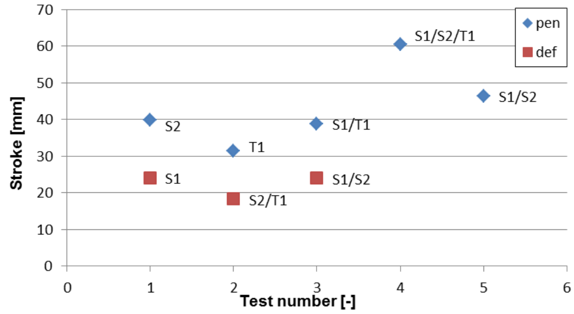

Fig. 17: max. stroke for each test case

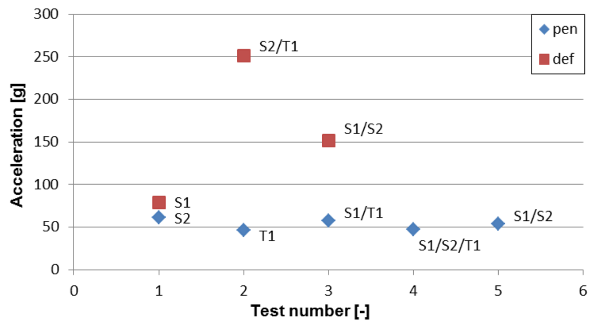

Fig. 18: max. Acceleration for each Test case

One can conclude that impacts on a deflector (mean: 22mm) produced approximately half of the deflection than with a penetrator (mean: 43mm). This is obvious because of the much smaller impact area of the penetrator.

The maximum accelerations for tests with the penetrator had only minor dispersions with an average of 53g over all test cases, while tests with the deflector produced at first higher but also a wider variance. Test case 5 & 6 had specifically high accelerations (251g resp. 152g). This can be explained by the alignment of the diagonal core beams. Test 5 & 6 were tests on the edge of two crash panels. For these cases the lander had to be inclined by 45° (see Fig. 19), so that the beams were perpendicular to the wall. This perpendicular alignment prevented the beams to bend properly.

Fig. 19: Impact view of test no. 5

The opening after each test worked as expected. However, it should be noted, that with each test both the lander body and the crash panel base plates deformed gradually more plastically. Due to this, during the last 2 tests the base plate standoffs lost physical contact with their counterparts and the cushion got jammed. This led to a malfunction of one panel while opening after test case 7.

VII. CONCLUSION & OUTLOOK

For this study a team from several companies contributed with their unique expertise to this project “Orbitallander”. Those were the SME companies GERADTS GmbH for the development of the unfolding mechanism and Materialise GmbH for the development of the 3D-printed core. The FIBRE institute of the University of Bremen supported the project with their ability to simulate the crash behavior and to laminate the face sheets with the core material. The DLR institute of Space Systems in Bremen was responsible for the project management, principal scientific investigation as well as for the final hardware testing. The work within the team was excellent so that in the end a final product was constructed.

All tests have been performed successfully. They all met the given requirements regarding impact velocity and attitude.

With regard to the test prediction (Fig. 5 and Fig.6 M1-10) it can be seen that the real tests produced slightly higher accelerations and lower displacements. Therefore the simulation needs to be correlated accordingly. Either the influence of the core or the face sheet has been underestimated, or both.

The unfolding after landing was demonstrated successfully, however in the lab tests a commercial-off-the-shelf linear actuator has been used, which was not always able to unlock the crash panels. For a flight system a space qualified wire cutter should be used, which can sustain higher impact forces and has no moving parts which could get jammed.

Because of the limited amount of test models only certain aspects could be addressed. This leaves open other questions. How will the lander behave for inclined impact cases and how is the landing dynamic in a realistic gravity environment when the lander can freely rotate around all axes?

These and other questions will be addressed in additional system design studies, numerical simulations as well as in additional laboratory tests.

VIII. REFERENCES

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